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An agent based approach to the potential for rebound resulting from evolution of residential lighting technologies

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Abstract
Purpose More energy efficient lighting options, such as compact fluorescent bulbs and light emitting diodes are predicted to significantly reduce the amount of energy used for lighting. Such forecasts are predicated on the assumption of light saturation and do not take into account the potential for economic rebound. The potential of the rebound effect to reduce or negate predicted energy savings is explored here.
Methods This work uses an agent-based model with a cellular automata approach to study the impact of rebound on the consumption of residential light and associated energy use, using three lighting technologies, and a time span from 2012 to 2030. Agents, representative of households, select between three lighting options using a multiplicative utility function and a probabilistic choice mechanism. Agents then decide whether to consume more light and potentially more energy based on the lighting technology selected and personal preferences. The agents are heterogeneous in nature, consisting of seven typologies, with their characteristics informed through survey data.
Results and discussion The results of the model indicate that although the consumption of light may increase, overall changes in the consumption of energy compared to 2012 levels will be minor. If the consumption of light is held steady, assuming saturation, then there is the potential for the adoption of energy-efficient lighting to result in significant energy savings. However, if the rebound effect occurs, there will be a decrease in the consumption of energy for lighting as consumers adopt more energy efficient options. Overtime as the consumption of light continues to increase, those savings will largely be eroded.
Conclusions This study suggests that the adoption of energy-efficient lighting in itself will not reduce the overall consumption of energy for lighting on a long-term scale although it may be successful in doing so in the short-term. The rebound effect will greatly reduce the projected energy savings from more efficient lighting technologies, with potential for direct rebound to exceed 100 %. In order for the quantity of energy utilized in residential lighting to decrease, solutions beyond that of efficiency gains must be considered.

Keywords Agent-based modeling · Energy efficiency · Light emitting diode · Lighting · Rebound effect · Residential consumption

1 Introduction

Light consumption in the USA represents a significant contribution to the national energy consumption. In 2010, lighting in the USA consumed 694 terawatt-hours (TWh) of energy (Navigant 2012a) or 7.4 quads of primary energy, which is equivalent 7.6 % of total energy consumption or 18.8 % of total electricity consumption (US EIA 2011). Light emitting diode (LED) lamps[1] represent an evolution in how residential

[1] Light emitting diode installations are typically referred to as "lamps;" however, for simplicity in this work, they will be referred to as "bulbs," in order to achieve consistent terminology usage.

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consumers meet their lighting needs. A 60-W incandescent equivalent LED uses on average one fifth of the energy of a comparable incandescent light bulb to produce approximately the same amount of light. This increased efficacy, coupled with a longer lifetime, has the potential to significantly lower the ownership cost of lighting and to reduce the amount of energy that is used. Under optimistic scenarios residential energy consumption for light is expected to decrease from 173 TWh in 2010 to 153 TWh in 2030 (Navigant 2012a). Such predictions of reduced energy demand, however, are predicated on the assumption of residential light consumption being at saturation, meaning that regardless of an increase in the efficiency of lighting and a subsequent decrease in the ownership cost, the consumption of light for the purposes of illumination will grow only with anticipated increases in inhabited spaces.

However, there is considerable evidence indicating that the consumption of light has not yet reached saturation and that there is the potential for direct economic rebound to occur as the price of light declines (Navigant 2012a; US EIA 2011). Direct rebound has been observed over a long-time span for lighting in the UK (Fouquet and Pearson 2006) and in other industries (Dahmus and Gutowski 2010). This has implications not only for the consumption of light but also for the environmental and societal impacts associated with light. The rate of light consumption has also accelerated over time. For example, in the UK, the annual consumption of light was about 1,534 lumen-hours per capita in 1750, increasing in 2000 to 16.72 million lumen hours per capita, an increase by a factor of 11,000 over 250 years (Fouquet and Pearson 2006). This increase encompassed periods of technological change for lighting, including the invention and adoption of candles, whale oil, gas, kerosene, and electric lighting. Dahmus and Gutowski (2010) reviewed historical consumption and efficiency trends across several basic goods and services and found short periods of reduced consumption when technological innovation has been coupled with incentives, such as efficiency mandates and price mechanisms but that overall consumption increases were significantly greater than efficiency gains.

Lifecycle studies of lighting have examined impacts over the stages of material acquisition, manufacturing, use/reuse, and end of life with the consensus that for all three of the lighting types considered here, incandescent, compact fluorescent light (CFL), and LED, the use phase will have the greatest impact (Gydesen and Mainmann 1991; Ramroth 2008; OSRAM 2009; Navigant 2012b; Welz et al. 2011). Although LED bulbs are more resource intensive to produce than CFL and incandescent bulbs, the longer lifetime and greater efficiency ensure that the use phase is where the majority of lifecycle impacts occur. The disproportionately large impact of the use phase suggests that this phase bears further investigation beyond the bounds of conventional LCA methodology to better understand how consumers use light.

Multiple approaches exist for modeling the behavior of complex systems, such as the adoption of energy-efficient lighting. For example, system dynamics represent a method of describing complex systems through a series of feedback loops and aggregate values and are mathematically at its core a set of differential equations (Borshchev and Filippov 2004). In agent-based modeling (ABM), a form of bottom up modeling, the actions of individuals are modeled, and it is those actions that collectively generate the overall trends and results. The main difference between the two modeling approaches is that in system dynamics, a central set of equations controls all flows, whereas in ABM, each individual or agent is acting autonomously. In terms of consumer adoption of energy-efficient lighting, which is largely an individual decision influenced through many factors, an ABM approach is a logical methodology to apply.

Cellular automata are a method of simulation which falls under the umbrella of ABM; however, the origination of the methodology evolved prior to the use of wide availability of high-speed computers, such as Schelling's segregation model (1969). In cellular automata models, the agents are a grid of cells, each with discrete states which evolve over time (Wolfram 1983). Interactions occur with "neighbors," the agents in the vicinity, and influence the choices of those agents. Agents change their states based on a set of overall rules and typically seek a common goal (Miller and Page 2007).

ABM has been used as part of a system's framework to study issues such as energy market and greenhouse gas emission simulation (Batten 2009), urban development (Baynes 2009), metal demand flow systems (Bollinger et al. 2011), energy infrastructure (Davis et al. 2009; DeLaurentis and Ayyalasomayajula 2009), air transport network (Keirstead and Sivakumar 2012), and crop modeling (Miller et al. 2013). Chappin and Afman (2013) have studied residential lighting using ABM, where a link and node network was used to simulate the effects of the European Union ban on incandescent light bulbs in the Netherlands (Afman 2010) and was largely influenced by economic drivers. The work presented in this paper employs a cellular-based approach with multi-criteria evaluation of lighting options to model the adoption of energy-efficient lighting technologies representative of urban areas in the USA.

1.1 Research questions

CFLs and LEDs represent an evolution in the technology of lighting. Contrary to conventional thought, there is the potential for the amount of light and energy consumed to increase as a reaction to the adoption of energy-efficient lighting technology. This work seeks to investigate the impact of the diffusion of energy-efficient lighting technology through a residential population.

2 Methods

The approach used in this paper seeks to understand those factors affecting decisions by agents to choose among three lighting technologies, incandescent, CFL, and LED. The model space is composed of a grid of 2,601 (51 by 51 agents or grid coordinates set from −25 through 25) heterogeneous agents, each representing a household. In the cellular automata approach used, agents change their lighting technology based on maximizing an individual utility function. The technologies are represented through illumination bulb choices that agents are given; in this model, all alternatives are 60-W incandescent equivalents and are representative of the options available today that would fit interchangeably into the same lamp socket. The specifications used for bulbs are incandescent (price—$1.17, lifetime—1,500 h, light output—830 lm, power usage—60 W), CFL (price—$1.59, lifetime—8,000 h, light output—825 lm, power usage—13 W), and LED (price—$33.99, lifetime—25,000 h, light output—800 lm, power usage—12 W) (Bulbs.com 2012). Initial lighting technologies, hours of use, and agent typologies were assigned from survey data encompassing four major urban areas in the USA: Chicago, Houston, New York, and San Francisco. Table 1 presents agent information on typologies which were derived from the relative importance of six factors identified when selecting a new lighting technology; further information on the derivation of these factors and treatment of the survey data is included as Electronic supplementary material 1.

In Table 1, agents are grouped by the factor that was self-identified as most important. Attributes of the majority of the agents in each group were then applied to the group as a whole. The largest group (type 1), representing 38.37 % (998 agents) consists of those who identified saving money as the most important reason to adopt a new lighting technology. Interestingly, only 8.82 % of the respondents (type 3) indicated environmental considerations as the most important reason to adopt energy-efficient lighting technology. This is relevant due to the adoption of CFL and LED lighting technology commonly advertised from an environmental perspective. The relative rankings are used to determine the weights of each factor in the utility equation for each lighting technology. It is assumed that the purchase price of LED bulbs will decline over time from their maximum price ($33.99) on a trajectory similar to that of CFLs. Survey data indicated that 50.2 % of agents (1,305), if given the opportunity, would consume more light if the technology reduces ownership costs, while 8.4 % (218) would sometimes consume more light, in effect flipping a coin when the opportunity arises.

Following Fig. 1, each agent makes a decision on the type of lighting technology to adopt at “opportunity moments,” defined by the lifetime of a burned out bulb, meaning that it has met or exceeded its manufacturer’s stated lifetime of hours in use. If the bulb has not exceeded its lifetime, then the agent keeps the bulb for the rest of the turn and consumes the same amount of light and energy as on the previous turn. If the bulb has burned out, then the agent evaluates the utility of all three lighting technology options. A Cobb–Douglas utility function is used, the general form of which is given by

$$U_i = \prod_{i=1}^{n} F_i^{w_i} \tag{1}$$

where U_i is the utility of the technology, f_i is the normalized score of the factor or characteristic of relative importance to the agent, such as purchase price, and w_i is the weighting of the factor (informed with survey data). Tsao et. al. (2010) suggested that an exponential function such as Eq. (1) is appropriate for modeling the consumption of light and energy.

The utility of each lighting technology option is used to determine the probability of adoption according to

$$P_T = 1 = \sum_{i=1}^{L} P_i = \frac{e^{U}i}{e^{U}i + e^{U}i + 1 + e^{U}i + 2 + \cdots + e^{U}L} \tag{2}$$

where P_i is the probability of technology i being selected, based on the utility of bulb i to that particular agent. The probabilities of selection of the three lighting technologies sum to 1, meaning that the probability of one of the lighting technologies being selected is certain. An option is then drawn using the Roulette Wheel Selection Method, a commonly used method for choice in ABM (Huang and Levinson 2009; Said et al. 2002), and the corresponding lighting technology is adopted. In this case, each of the lighting technologies form a portion of the agent’s selection wheel, the probability of the technology being selected, defines how large its representation on the selection wheel is. The wheel is updated every time the agent evaluates the utility of the lighting options, spinning the wheel selects a lighting option.

Once a new technology has been selected, the agent compares the new technology with the old technology. If the new and old technologies are the same, then the same amount of light and energy is consumed as the previous term. If the bulb technologies differ, then the difference in efficacy determines the subsequent light and energy consumed. If the old technology has a greater efficacy, then the same amount of light, but more energy, will be consumed. If the efficacy of the new technology is greater, then the amount of light consumed will depend on the agent’s predisposition to consuming more light, more light translating to potentially greater energy consumption.

Table 1 Agent typologies based on survey data (1=most important, 6=least important)

Typology	1	2	3	4	5	6
Percentage of Agents	38.37	29.7	8.82	5.67	8.83	8.61
Saving money through use	1	3	2	2	2	2
Saving energy	2	1	3	3	3	3
Environmental considerations	3	2	1	4	4	4
Influence of others	4	4	4	1	6	6
Initial purchase cost	5	5	5	5	1	5
Performance (color temperature)	6	6	6	6	5	1

3 Results and discussion

3.1 Light and energy consumption

In order to better understand the potential impacts of different policy interventions and mechanical attributes, five scenarios were selected and are presented in Table 2 and Fig. 2a, b. A sensitivity analysis of this ABM may be found in Electronic supplementary material 2.

Scenario 1 assumes that the light consumption is at saturation, meaning that agents will not consume more light irrespective of the choice of lighting technology. This results in a corresponding decrease in energy use due to the increased efficacy of the population's lighting stock. Scenario 2 is identical to 1 except that, when given the opportunity, an agent will consume 25 % more hours of light than the agent currently does. This results in an overall increase in the amount of light consumed and a slight overall increase in the amount of energy consumed. The initial decline in energy consumption, as shown in Fig. 2b, is due to those agents who select more efficient lighting technologies. Scenario 3 introduces a subsidy to the LED bulbs of 25 % of the purchase price, thereby lowering their capital cost. For scenario 4, the possibility of premature failure of LED bulbs, a problem well-documented for CFLs, is introduced (Pacific Northwest National 2006; Ramroth 2008). It is therefore assumed that agents will consume 25 % more hours of light and 25 % of LED bulbs per year fail before the end of their expected life. Scenario 5 is similar to no. 2, except agents consume 50 % more hours of light.

As shown in Fig. 2a, b, scenarios 2 and 3 exhibit similar patterns for the consumption of light and energy. In scenario 1, the light consumption is static, as guaranteed by the assumption of saturation, and the energy consumption decreases with the adoption of more energy-efficient lighting technology. Scenario 5 assumes that agents use 50 % more hours of light compared to the 25 % assumed in scenarios 2, 3, and 4. This causes the energy and light consumption to follow similar initial patterns as scenarios 2 and 3 but results in eventual greater amounts of energy and light consumption. Scenario 4, where 25 % of the LEDs fail early each year, exhibits a pattern of light consumption similar to scenarios 2 and 3 but with slightly greater consumption. From an energy consumption perspective, the energy used does not drop as significantly as in four other scenarios. This may be due to the shortened lifetime of the LED bulbs causing greater switching of lighting types than would occur otherwise. The results of these scenarios suggest that subsidies and early failure will have small impacts on the ultimate consumption of light and that

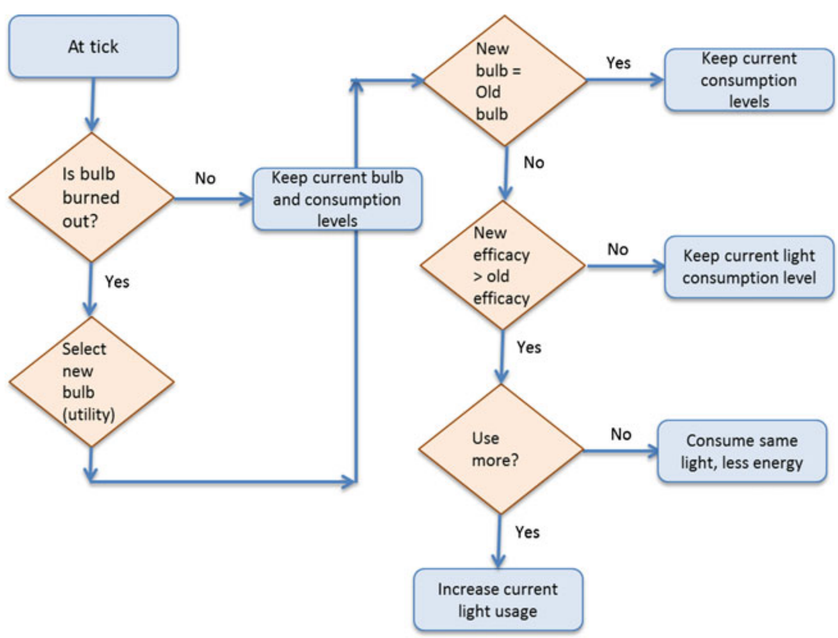


Fig. 1 Flow chart of agents' actions per turn, each turn being representative of 1 year

Table 2 Five scenarios influencing the adoption of energy efficient lighting

Scenario Number	Scenario Description
1	All bulbs are new in 2012, agents consume 0 % more light
2	Same as 1, but agents consume 25 % more light
3	Subsidy of 25 %, agents consume 25 % more light
4	Same as 2, but 25 % of LEDs fail early
5	Same as 2, but agents consume 50 % more light

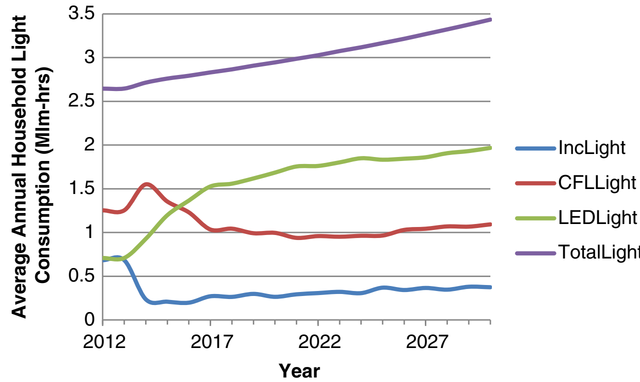


Fig. 3 Light consumption by scenario 2 by lighting type

there is potential for the increase in energy consumption to exceed anticipated reductions in energy use associated with more energy-efficient lighting technologies.

Figure 3 presents the evolution of technological adoption of more energy-efficient lighting technologies, as illustrated by scenario 2. Incandescent light consumption decreases with the adoption of CFL and LED bulbs. CFL light consumption initially increases with the switch from incandescent and then begins to decrease with the increased adoption of LED lighting. LED lighting usage initially increases slowly and then begins to increase rapidly with the shift from CFL to LED. For this scenario, this contributes to an overall increase in light consumption. Such a trajectory from incandescent to CFL and finally LED, found for all scenarios investigated in this study, is consistent with the findings by other studies (Navigant 2012a; Navigant 2010).

3.2 Economic rebound calculations

Direct economic rebound has the potential to decrease the energy savings from the adoption of energy-efficient lighting technology. When rebound exceeds the pre-adoption baseline, then economic backfire has occurred. The economic rebound coefficient, R, over the time period of interest is calculated using Eqs. (3) and (4).

$$\langle R \rangle = + \frac{r}{\lambda_E} \tag{3}$$

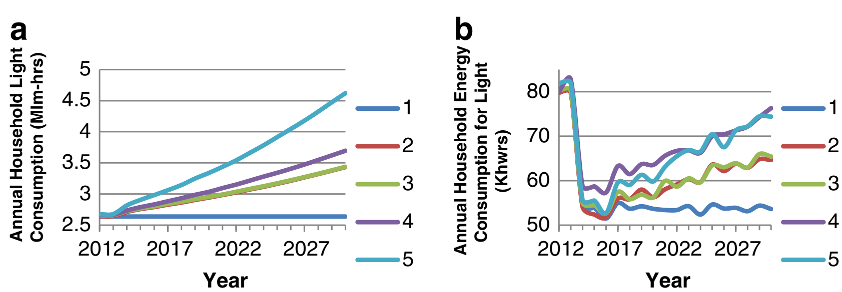
where r is the annual growth rate of energy use, and λ_E, the efficacy improvement, is given by

$$\lambda_E = ln\left(\frac{\tau_{18}}{\tau_0}\right) \Big/ (2030 - 2012) \tag{4}$$

where τ represents the efficacy of the lighting technology (2012 incandescent and 2030 LED). A more detailed explanation of rebound calculations along with examples may be seen in Electronic supplementary material 3.

Rebound values were calculated for the four scenarios where light consumption increases with results as follows: 2 (0.87), 3 (0.87), 4 (0.97), and 5 (0.94). R equals 1 is complete rebound, R greater than 1 means that backfire is occurring). For R less that 1 (scenarios 2, 3, 4, and 5), partial rebound is occurring. This means that some of the potential energy savings from efficiency gains will be consumed by increases in light usage. These results are consistent with a study by Tichelen (2009), where rebound values were computed across eight scenarios, ranging from 1.72 (business as usual scenario) to 0.46 (best available technology scenario). Such a phenomenon is consistent with historical rebound values for lighting and accords with previous studies (Tsao and Waide 2010; Gillingham et al. 2012; Druckman et al. 2011; Greening et al. 2000).

Fig. 2 **a** Household level light consumption from the 5 scenarios presented, each is an average of five model runs and **b** household level energy consumption from the 5 scenarios



4 Conclusions

It should be stressed that agent-based models are not generally intended to be quantitatively predictive. Rather they allow for the exploration of scenarios, and their potential impacts. In this study, given realistic information on lighting efficacies, and plausible behavioral patterns as revealed through surveys, there appears to be considerable potential for increased illumination as lighting technologies continue to evolve. If direct rebound does not occur, then increases in lighting efficiency certainly have the potential to decrease energy consumed for lighting. However, if efficiency gains and lighting consumption increases are coupled, there is the potential for the projected energy savings to be reduced or even negated. Since the utility of lighting will undoubtedly increase while prices continue to fall, much of this discussion on this issue revolves around the concept of lighting saturation, which itself consists of two factors. First, that lighting density to satisfy consumer demands is no longer increasing and second, that the amount of time that artificial lighting is being used will not increase in the future. This paper has explored the second aspect of saturation, that of duration. Whether or not greater lighting efficacies will result in higher illumination levels remain to be thoroughly investigated.

Against the trends reviewed in this paper must be balanced the gains to individuals and society of greater light consumption, whether of intensity or duration. The ability to turn dark or dimly lit spaces into areas of greater productivity, safety, and comfort with gains in individual satisfaction has been demonstrated historically many times over (Tsao et al. 2010; Fouquet and Pearson 2006). Whether such advantages will continue as lighting technologies evolve are areas for further exploration.

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